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# IGNEOUS FRACTIONATION AND SUBSOLIDUS EQUILIBRATION OF DIOGENITE METEORITES. David W. Mittlefehldt, C23, Lockheed Engineering and Sciences Co., 2400 Nasa Rd. 1, Houston, TX 77058.

Diogenites are coarse-grained orthopyroxene breccias of remarkably uniform major element composition. Most diogenites contain homogeneous pyroxene fragments up to 5 cm across [1] of  $\text{Wo}_{25}\text{En}_{74}\text{Fs}_{24}$  composition. Common minor constituents are chromite, olivine, troilite and metal, while silica, plagioclase, merrillite and diopside are trace phases. Diogenites are generally believed to be cumulates from the eucrite parent body [2], although their relationship with eucrites remains obscure. It has been suggested that some diogenites are residues after partial melting [3]. I have performed EMPA and INAA for major, minor and trace elements on most diogenites, concentrating on coarse-grained mineral and lithic clasts in order to elucidate their igneous formation and subsequent metamorphic history.

**Minor and Trace Element Correlations.** Although diogenite orthopyroxene grains are very uniform in major element composition, they exhibit a wide range in minor, incompatible element contents. Excluding Yamato Type B diogenites (Y-75032-type),  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  vary by factors of 7 and 4, respectively. Among the majority of diogenites,  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  are strongly correlated (Fig. 1), as would be expected for cumulus orthopyroxene grains formed from an evolving magma. Correlation between minor elements determined by EMPA and trace elements determined by INAA is not as straightforward because a small amount of crystallized trapped liquid may affect bulk analyses. Among the *incompatible* trace elements determined by INAA, Sc and Yb concentrations will be least affected by a trapped liquid component because they have the highest opx/melt partition coefficients [4]. Both  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  are correlated with Sc and Yb for most diogenites (Fig. 1;  $\text{TiO}_2$  correlations not shown). Excluding unusual diogenites (labeled in Fig. 1), Sc varies by a factor of 2, and Yb by a factor of 9. These correlations also indicate that diogenites record an extensive igneous fractionation sequence. Individual diogenites can show a wide range of incompatible element contents. However, in EETA79002 most orthopyroxenes have a limited range in minor element content (Fig. 2), suggesting that brecciation may have mixed in pyroxenes from different regions of diogenite lithologic unit(s); i.e. EETA79002, and perhaps other diogenites, may be genomict breccias. This is also suggested by major element compositions of EETA79002 orthopyroxenes (see below).

**Major Element Uniformity.** The igneous fractionation inferred from minor and trace elements is at odds with the general uniformity in molar  $100 \times \text{MgO}/(\text{FeO} + \text{MgO})$  (hereafter mg#) in the diogenite suite. The majority of diogenites have mg# of  $\sim 75$ , which implies minimal igneous fractionation (Fig. 3). These same diogenites vary in incompatible trace elements ( $\text{TiO}_2$  - 0.03 to 0.14 wt%; Sc - 9.8 to 18.1  $\mu\text{g/g}$ ; Yb - 30 to 290 ng/g; Fig. 3), which implies extensive igneous fractionation. Weak positive correlations between  $\text{Cr}_2\text{O}_3$  and mg# have been shown for some diogenite orthopyroxenes, indicating that evidence for igneous fractionation is partially preserved in diogenite major element compositions [5]. For comparison, cumulus orthopyroxene grains from the Upper Bronzite Zone of the Stillwater Complex generally show the expected increase in  $\text{TiO}_2$  and Yb with decreasing mg# resulting from igneous fractionation [6]. The observed scatter in  $\text{TiO}_2$  and Yb relative to mg# for Stillwater cumulus orthopyroxenes (Fig. 3) has been attributed to partial subsolidus equilibration of Fe and Mg [6].

**Unusual Diogenites.** Several diogenites are distinct from the majority. Manegaon is the most primitive diogenite; it has the highest mg# (78.5) and lowest Sc content (9.1  $\mu\text{g/g}$ ) (Fig. 3). However, Manegaon orthopyroxene contains the highest  $\text{Al}_2\text{O}_3$  content (1.34 wt%) (Fig. 1), which would suggest it originated from the most evolved parent magma. Manegaon is anomalously low in  $\text{TiO}_2$ , Yb and especially Sc for its

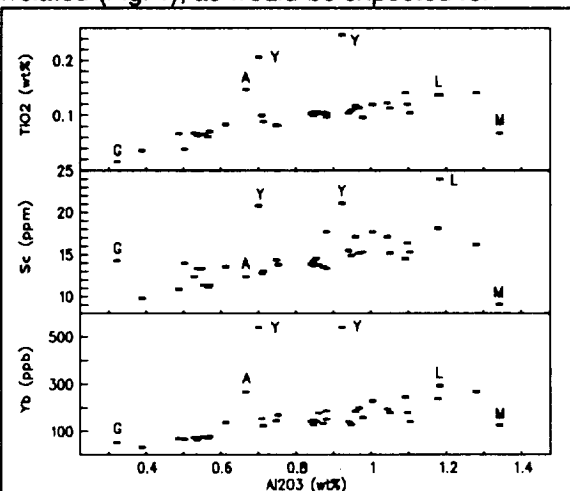


Fig. 1. Trace and minor element compositions of diogenite orthopyroxenes. Labeled diogenites are; A - ALH84001, G - Garland, L - LEW88008, M - Manegaon, Y - Yamato Type B.

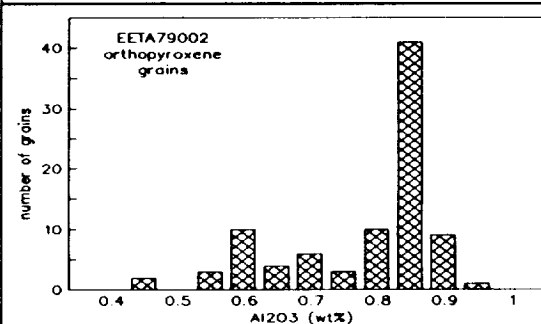


Fig. 2. Histogram of  $\text{Al}_2\text{O}_3$  contents of individual EETA79002 orthopyroxene grains.

# **DIAGENITE METEORITES, David W. Mittlefehldt**

$\text{Al}_2\text{O}_3$  content (Fig. 1). Therefore, Manegaon was probably not formed from the same parent melt as other diogenites. ALH84001, Garland, LEW88008 and Yamato Type B diogenites are more ferroan than typical diogenites (Fig. 3), implying that they were formed from more evolved parent melts. Garland orthopyroxene, however, contains the lowest  $\text{TiO}_2$  (0.02 wt%) and  $\text{Al}_2\text{O}_3$  (0.32 wt%) contents of any diogenite, and the second lowest Yb content (50 ng/g) (Fig. 1). These low incompatible element contents suggest that Garland's parent melt was more primitive than that of the majority of diogenites. Garland also has an anomalously high Sc content for its generally low incompatible element contents and has the highest Sc/ $\text{Al}_2\text{O}_3$  ratio of any diogenite (Fig. 1). ALH84001 and the Yamato Type B diogenites have unusually high  $\text{TiO}_2/\text{Al}_2\text{O}_3$  and Yb/ $\text{Al}_2\text{O}_3$  ratios (Fig. 1), and were probably formed from different parent magmas than the majority of diogenites. Chromite grains from ALH84001 and Yamato Type B diogenites contain high  $\text{TiO}_2$  contents, about 3 times those of other diogenites, and Yamato Type B diogenites contain ilmenite as well [7]. Hence, these diogenites were likely formed from unusually  $\text{TiO}_2$ -rich magmas. Yamato Type B diogenites contain a significant amount of crystallized trapped liquid [7,8], and therefore, trace element contents are difficult to evaluate in relation to the EMPA data. LEW88008, in addition to being the second most ferroan diogenite (Fig. 3), is rich in all the incompatible elements (Fig. 1) and is a plausible Fe-rich differentiate of the diogenite parent magma.

**Thermometry and Subsolidus Equilibration.** Mineral phases in diogenites can be used to calculate equilibration temperatures using two-pyroxene thermometry [9], and orthopyroxene-spinel thermometry [10]. Two-pyroxene thermometry yields temperatures ranging from about 900°C for ALHA77256 to about 620°C for Ibbenbüren (Table 1). Diopside grains are generally small, on the order of 10-20  $\mu\text{m}$ , and were formed by subsolidus exsolution from the orthopyroxene host [11]. Orthopyroxene-spinel temperatures are in the range of 880°C to 640°C (Table 1), except for higher temperatures for Tatahouine, 960°C, and Yamato Type A diogenites (Y-74013-type), 1050°C [7]. Large, mm-sized chromite grains record higher equilibration temperatures than do small, < 100  $\mu\text{m}$  chromite grains (Table 1). The low orthopyroxene-clinopyroxene and orthopyroxene-spinel temperatures indicate subsolidus equilibration of major elements in diogenites. This equilibration predated brecciation; in EETA79002 magnesian orthopyroxene (mg# 81) is in breccia contact with typical orthopyroxene (mg# 76), again suggesting that this is a genomict breccia.

**Summary.** Major element compositions of diogenites are decoupled from minor and trace element compositions; the latter record an igneous fractionation sequence that is not preserved in the former. Low equilibration temperatures indicate that major element diffusion continued long after crystallization. Diffusion coefficients for trivalent and tetravalent elements in pyroxene are lower than those of divalent elements [e.g. see 6]. Therefore, major element compositions of diogenites may represent means of unknown portions of a cumulate homogenized by diffusion, while minor and trace elements still yield information on their igneous history. The scale of major element equilibration is unknown, but is likely to be on the order of a few cm [e.g. see 6]. Therefore, the diogenite precursors may have consisted largely of cm-sized, igneously zoned orthopyroxene grains, which were subsequently annealed during slow cooling, obliterating major element zoning but preserving minor and trace incompatible element zoning.

**References.** [1] Mason (1963) *Am. Mus. Nov.* 2155, 13pp. [2] Fukuoka *et al.* (1977) *PLSC 8th*, 187. [3] Sack *et al.* (1991) *GCA* 55, 1111. [4] Colson *et al.* (1988) *GCA* 52, 539. [5] Berkley and Boynton (1992) *Meteoritics* 27, 387. [6] Lambert and Simmons (1987) *AJS* 287, 1. [7] Mittlefehldt and Lindstrom (1993) *Proc. NIPR Symp. Ant. Met.* 6, submitted. [8] Takeda and Mori (1985) *PLPSC 15th*, C636. [9] Lindsley and Anderson (1983) *PLSC 13th*, A887. [10] Mukherjee *et al.* (1990) *PLPSC 20th*, 299-308. [11] Mori and Takeda (1981) *EPSL* 53, 266-274.

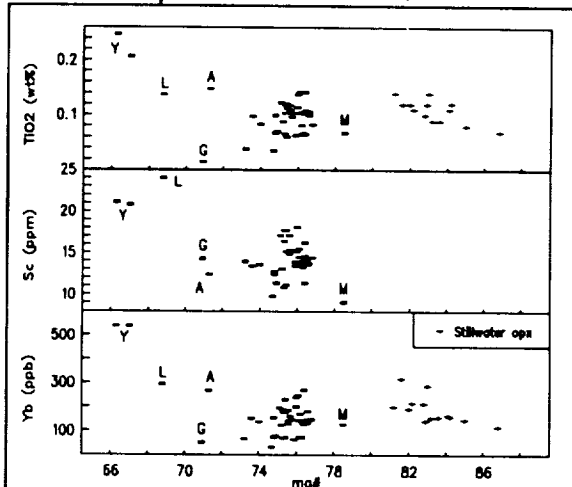


Fig. 3. Minor and trace element variations with mg# in diogenite orthopyroxenes. Labels as in Fig. 1. Cumulus orthopyroxene from the Stillwater Complex Upper Bronzite Zone [6] are shown for comparison.

Table 1. Equilibration temperatures (°C) of diogenites.

		opx-sp	opx-cpx
Ajoun el Atrouss			750
ALHA77256	large cm	790	900
	small cm	780	
ALH84001		720	
EETA79002		750	
Garland		880	
Ibbenbüren			620
Johnstown		640	
Manegaon		650	750
Roda			880
Shalka	large cm	850	
	small cm	740	
Tatahouine		960	
TIL82410		680	
Yamato A	large cm	1050	
	small cm	840	
Yamato B		700	860